Standard Model Physics at the Large Hadron Collider (LHC)

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ABSTRACT

The Large Hadron Collider (LHC) is the most powerful hadron collider ever built and the Higgs boson, which is the last piece of the Standard Model, was discovered in 2012 using the data by the ATLAS and CMS experiments at the LHC. After the discovery, particle physicists have been conducting high precision testing of the Standard Model theory and such studies can provide indirect sensitivities to new physics.

In this article, the latest results for the precision measurements of the Standard Model from the ATLAS, CMS and LHCb experiments are presented. The highlights regarding the most significant measurements and their implications on new physics searches are discussed.

INTRODUCTION

The Large Hadron Collider (LHC) is the largest and highest energy collider in the world. It was built at CERN, from 1998 to 2008. The length of the LHC accelerator is 27 kilometers in circumference and the designed center-of-mass energy is 14 TeV. The main physics goals of the LHC have been to allow physicists to test the Standard Model (SM) through precision measurements, the discovery of the Higgs boson, and the searches for various beyond the Standard Model (BSM) theories to answer many unsolved questions of physics. The LHC started its first run from March 2010 to early 2013 at an energy of 7 and 8 TeV, and that period is now known as the Run-I period. After two years of shut-down for several upgrades, its second data-taking period (called Run-II) began in 2015 at the center-of-mass energy with 13 TeV.

The LHC has four cross points; four detectors, which have been designed for different purposes, are built in the points. The general purpose detectors are ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid). ALICE (A Large Ion Collider Experiment) is optimized to study heavy-ion (Pb-Pb nuclei) collisions. LHCb (Large Hadron Collider beauty) aims to study b-physics specially. The LHC's accelerator complex and the four detectors positioned at the LHC are described in Fig. 1. Fig. 2 shows a brief structural overview of the CMS detector (the ALTAS detector is similar) and its subdetectors.

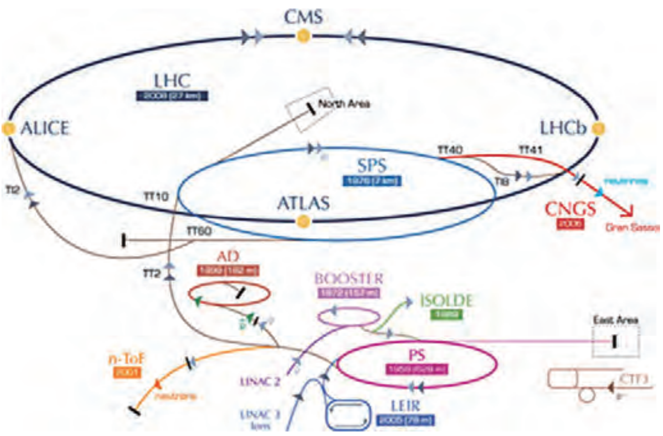

Fig. 1: Diagram of the LHC accelerator complex. Four large experiments (the ALICE, ATLAS, CMS and LHCb) are located at the LHC.

The Higgs boson (well-known as the "God Particle") has been discovered by the ATLAS and CMS collaborations in 2012 with the combination of 7 and 8 TeV data [1, 2]. This new particle has a mass with about 125 GeV and the

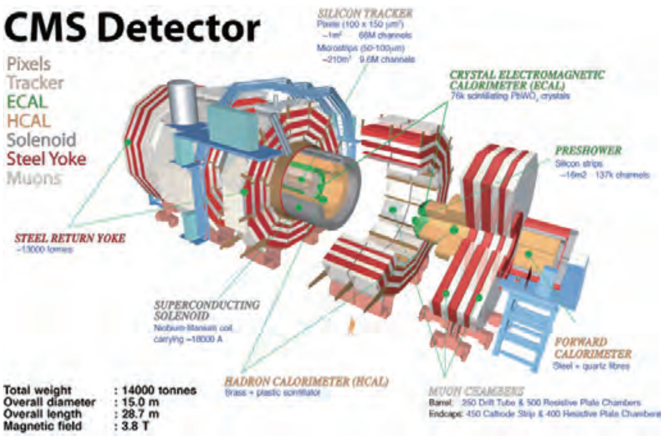

Fig. 2: Structure of the CMS detector and its subsystems.

properties including spin, decay channels etc. are similar to the SM prediction. It is also the first elementary scalar particle that has been discovered in nature and further studies of this particle are underway.

After the Higgs discovery, the next goal for physics at the LHC has been to find a hint of new physics. In addition, we have been collecting a huge amount of data and it has allowed us to test the SM theory with high precision measurements, particularly with rare decays. Understanding the SM processes accurately is crucial as they are major backgrounds for the BSM searches. Fig. 3 shows the summary of integrated luminosity collected by the CMS detector. As shown in the figure, the amount of data collected is dramatically increasing year-by-year and

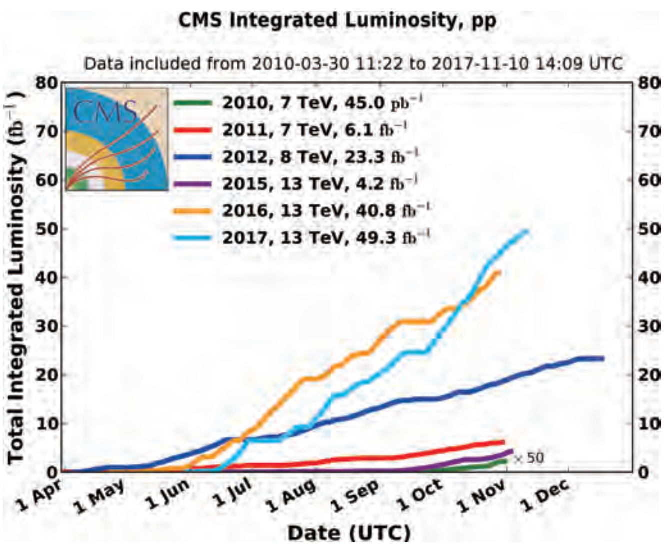

Fig. 3: Integrated luminosity collected by the CMS detector since 2010. The plot shows cumulative luminosity versus the date delivered to CMS during stable beams for proton-proton collisions at nominal center-of-mass energy. [3]

we expect about 300 – 500 fb^{-1} data up to the year 2023 (the upgrade plan after that year will be discussed later in the article).

In this article, the latest results for the precision measurements of the SM theories from the ATLAS, CMS and LHCb collaborations are discussed. There are several hundreds of publications for the SM precision measurements from the experiments so far, therefore we discuss only the best achievements as highlights.

PRECISION MEASUREMENTS

The electroweak (EWK) interactions are mediated by the W and Z gauge bosons (and the photon) in the SM. The W boson was discovered in 1983 at CERN with the SPS collider. The W boson has been studied deeply and precisely during more than three decades and the properties of the boson have been unveiled. Nevertheless, the ultimate precision measurement of the boson's mass is necessary. The W boson mass is connected to the existence of the Higgs boson and can constrain the Higgs boson mass with the top quark mass. If we observe the deviation from the constraint, it can indicate the contribution of BSM effects. Therefore, the precise measurement of the W mass tests the theoretical predictions of the SM.

The measurement is challenging at the LHC compared to LEP and Tevatron because first, the number of simultaneous interactions per a beam bunch crossing is much larger and second, W boson production is significantly influenced by the second generation quarks. In addition, to achieve the required level of precision as compared to the previous experiments, the measurement demands very accurate calibration and simulation modeling.

Recently, the ATLAS collaboration presented their results regarding W mass measurement with a 7 TeV dataset. They analyzed more than 10^6 W boson candidates in muon and electron channels respectively and obtained results compatible to LEP and Tevatron experiments. Fig. 4 shows the compatibility of the measured W mass in the context of the global EWK fit, using recent top quark and Higgs boson masses.

Another important parameter related to the W and Z bosons is the weak mixing angle, which can be written as $\sin^2\theta_W = 1 - M_W^2/M_Z^2$ and can be measured using the forward-backward asymmetry (A_{FB}) in Drell-Yan (DY)

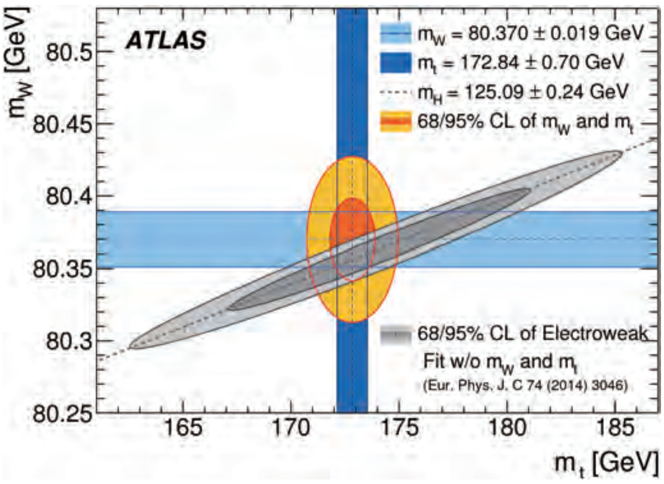

Fig. 4: The 68% and 95% confidence-level contours of the W mass and the top quark mass indirect determination from the global EWK fit are compared to the ATLAS measurements [4].

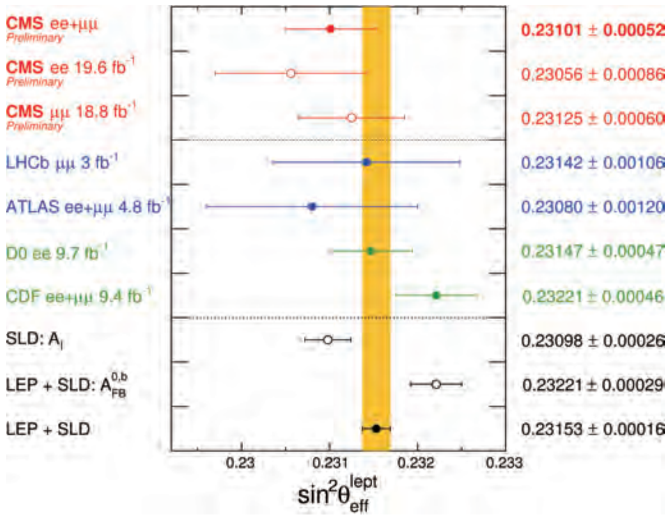

Fig. 5: Comparison of the measured weak mixing angle in the dilepton channels and their combination with the previous results. The shaded yellow band corresponds to the combination of the LEP and SLC measurements [5].

events. The A_{FB} is defined as $A_{FB} = (\sigma_F - \sigma_B)/(\sigma_F + \sigma_B)$ based on the angle θ* of the lepton in the Collins-Soper frame of the dilepton system.

The most precise results for the weak mixing angle were performed by the LEP and SLD experiments shown in Fig. 5. Both results have about three standard deviations; therefore, it is important to improve the measurements at LHC to better understand the parameter. Recently the CMS collaboration presented a new result for the weak mixing angle with an 8 TeV dataset. This result is the most precise achievement for the weak mixing angle at the LHC. Fig. 5 shows the result of the measured weak mixing angle at CMS with an 8 TeV dataset in the dimuon and dielectron channels and their combination. The results are in the pipeline of publication and the significant improvement is promising, with more statistics at 13 TeV.

MEASUREMENTS OF DIFFERENTIAL CROSS SECTIONS FOR THE DRELL-YAN PROCESS

The DY production with a lepton pair in hadron-hadron collisions is described in the SM by s-channel γ*/Z exchange. Theoretical calculations of the differential cross sections are well established up to next-to-next-to-leading order (NNLO) in quantum chromodynamics (QCD). Therefore, the DY process is an important SM benchmark channel allowing for tests of the NNLO perturbative QCD calculations. Furthermore, it is a major background for various BSM searches in the leptonic final state channels. Hundreds of GeV mass regions have never been explored in previous experiments. Consequently, precise measurements of the DY differential cross sections are crucial and comparison to NNLO theoretical predictions can improve our knowledge and allow for more precise modeling.

ATLAS and CMS experiments have measured the DY differential cross sections as a function of not only dilepton invariant mass but also other important variables like dilepton rapidity and transverse moments (and two dimensional measurements between variables) with 7 and 8 TeV datasets. The results have been compared to existing latest NNLO Parton Distribution Function (PDF) sets and have been used as an input dataset for the next generation of PDFs. Fig. 6 shows recent results for the DY measurements as a function of dilepton invariant mass spectrum. The results cover a range from 15 GeV to 2000 GeV with more than a 10^9 order scale on the y-axis. It is a triumph for both theoretical and experimental researchers in that we have achieved such precision with very good agreement in the results. This important measurement continues to be studied at Run-II.

MEASUREMENTS FOR DIBOSON AND MULTIBOSON PRODUCTIONS

Studies of diboson and multiboson productions are motivated to test EWK processes of the SM. In addition, such diboson and multiboson processes present as primary backgrounds in Higgs measurements and new physics

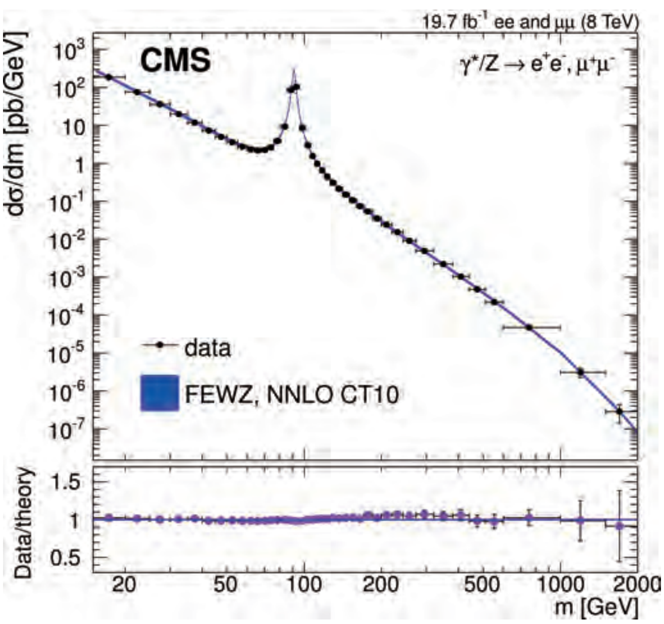

Fig. 6: The DY differential cross section as measured in the combined dilepton channel from the CMS experiment. The results are compared to the NNLO theoretical prediction calculated by the FEWZ program [6].

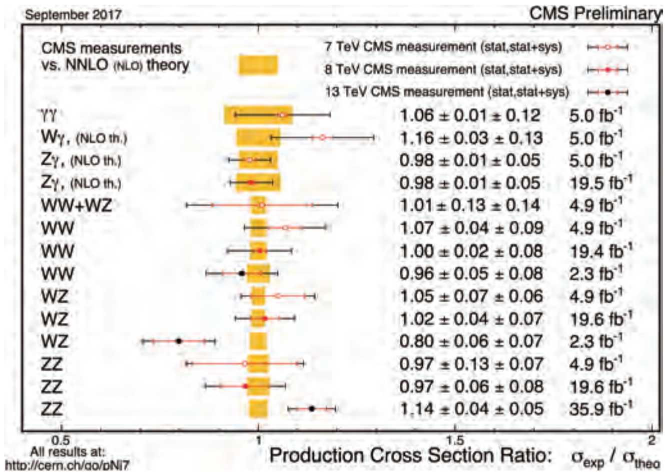

Fig. 7: Results for diboson cross section measurements with various channels from the CMS experiment and their comparison to the theory predictions calculated at NNLO [7].

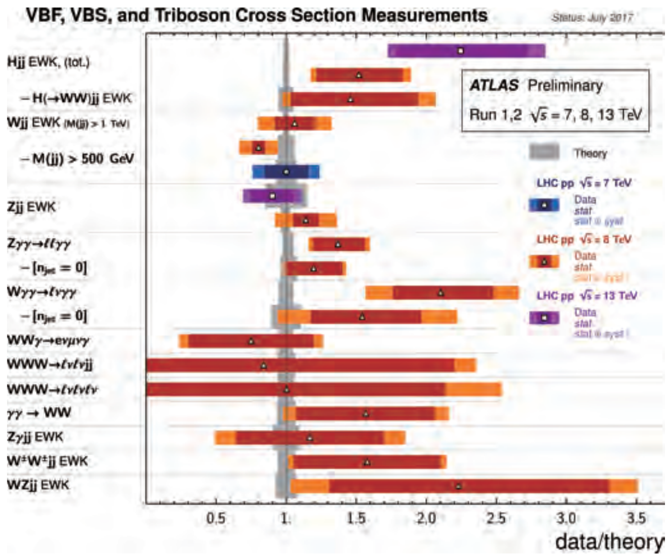

Fig. 8: Results for various vector boson fusion/scattering and triboson fiducial cross section measurements from the ATLAS experiment and their data/theory ratio. All theoretical predictions are calculated at next-to-leading order (NLO) [8].

searches, therefore it is important to understand their production cross section and properties. Another important point of the studies is to provide indirect sensitivities to BSM-like anomalous triple and quartic gauge couplings (aTGC and aQGC).

The measurements of the diboson production and single boson production via vector boson fusion allow access to rare processes and provide sensitive probes for aTGC. The measurements of triboson production and vector boson scattering do the same for aQGC. Various diboson processes like γγ, Wγ, Zγ, WW, WZ, ZZ etc., with and without jet association, are analyzed in many different decay channels with Run-I data in both the ATLAS and CMS experiments. Also, multiboson processes that produce more than two bosons, for instance, WWW, WWγ, and Wγγ etc., have been studied in both experiments. The results are summarized in Fig. 7, from the CMS, and Fig. 8, from the ATLAS, respectively and many other similar results including aTGC and aQGC interpretations are available in recent publications.

JET PHYSICS

QCD describes strong interactions among quarks and gluons. Inclusive jet production in proton-proton collisions provides a useful means to test perturbative QCD calculations over a wide region of phase space. Moreover, the production is sensitive to the value of the strong coupling constant, α_s, hence the measurement of the inclusive jet cross section can extract the α_s value precisely in a wide kinematic range like the TeV scale. Deviation of the strong coupling on the high momentum scale could appear due to the BSM effect and precise understanding of the parameter is crucial.

The ATLAS and CMS collaborations performed the measurements of the double-differential inclusive jet cross section as a function of jet transverse momentum (p_T) and absolute jet rapidity using 8 and 13 TeV data-

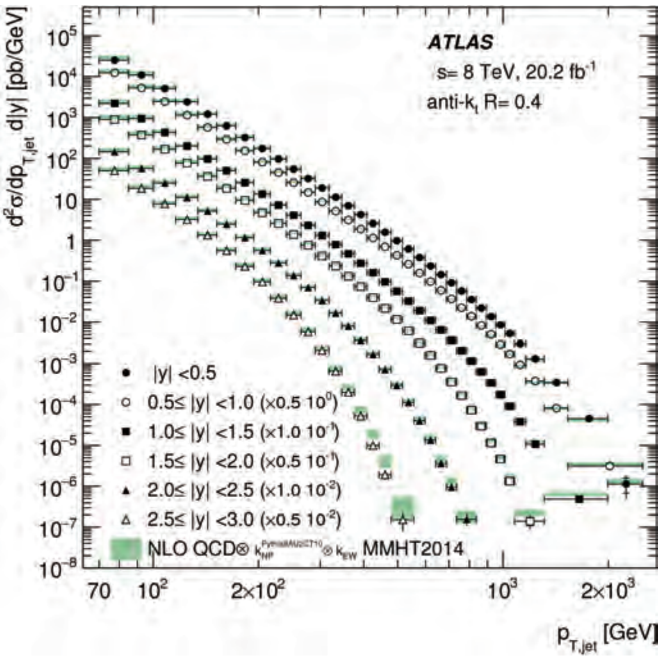

Fig. 9: Inclusive jet cross section as a function of jet p_T in bins of jet rapidity. The data results are compared to the NLO QCD prediction with the MMHT2014 PDF set corrected for non-perturbative and EWK effects [9].

sets. Understanding in the jet high p_T region is quite important for new physics searches.

Fig. 9 shows the recent results of a cross section measurement with an 8 TeV dataset from the ATLAS experiment. The measurements cover a wide jet p_T range above 2 TeV with separated jet rapidity bins and they are compared to the NLO QCD prediction with various corrections. The results are in a good agreement with the theoretical predictions.

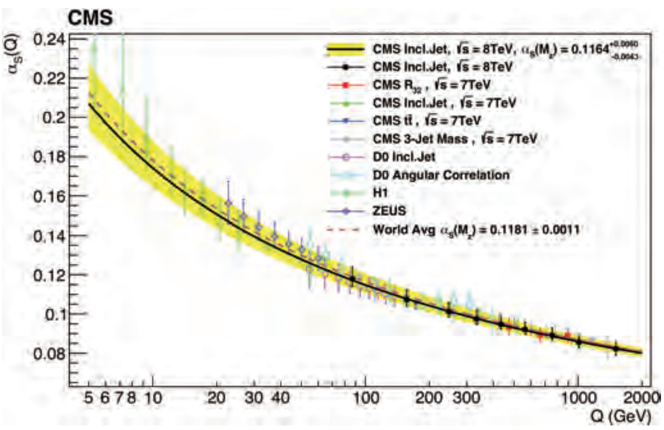

Fig. 10: The running α_s (Q) as a function of the scale Q determined by the CMS collaboration. This result is obtained by using the measurement of the inclusive jet cross section with an 8 TeV dataset and CT10 NLO PDF [10].

The measured differential cross section, and in particular, the high jet p_T region where the sensitivity to the value strong constant α_s is maximal, is used to extract the α_s in a wider kinematic range with higher accuracy. This extraction uses the CT10 NLO PDF set in the theoretical calculation because this PDF set provides the best agreement with the measured cross sections from the data. Fig. 10 shows the recent result of the α_s extraction from the CMS collaboration with 8 TeV data. The results from other experiments are superimposed in the figure.

BOTTOM-QUARK PHYSICS

Studies for physics related to the b-quark have been performed by B-factory experiments like the BELLE experiment. Such experiments performed CP violation, rare decays of the SM, searches for exotic particles and precision measurements of the B and D mesons, etc. Nevertheless, several interesting studies could be done with the LHC data. For instance, the B meson state with heavier quarks like Bs can be studied only with the LHC data.

The probabilities or branching fractions (BFs) of $B_s^0 \rightarrow \mu\mu$ (and similarly $B^0 \rightarrow \mu\mu$) are especially interesting because this decay channel is sensitive to various BSM theories. The SM predicts that this decay channel is very rare (the BF of the B_s^0 is the order of 10^{-9}). Therefore, a difference in the observed BFs with respect to the SM prediction would provide indirect evidence of the BSM contribution.

The CMS and LHCb collaborations jointly performed an analysis of the data collected during 2011 and 2012 and reported the first observation of the $B_s^0 \rightarrow \mu\mu$ with more than six standard deviations and the $B^0 \rightarrow \mu\mu$ with

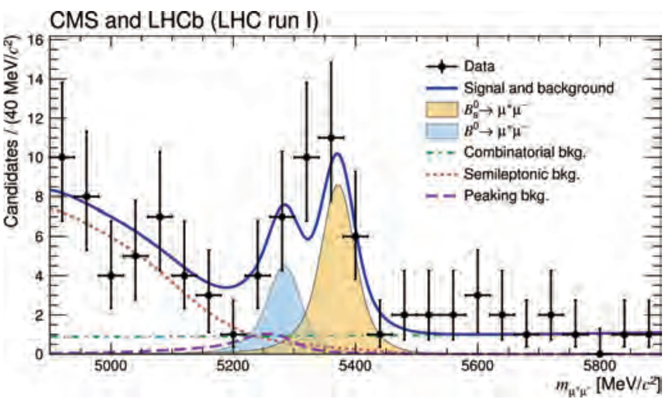

Fig. 11: Distribution of the dimuon invariant mass and observation of B^0_s and B_0 contributions in the combination of the CMS and LHCb datasets [11].

three standard deviations with a statistical significance, as shown in Fig. 11. The results are statistically compatible with the SM predictions and provide stringent constraints for BSM theories.

TOP-QUARK PHYSICS

The top quark is the heaviest known elementary particle in the SM and its unique properties have played a key role in solving several open questions in nature. The top quark was discovered in 1995 by CDF and D0 collaborations at the Tevatron experiment. However, a more precise understanding regarding the properties of the top quark is still needed.

The LHC accelerator is a kind of top quark factory with proton-proton collisions and allows precise measurements for the properties of top quarks, inclusively and differentially, to be taken. An intensive physics program for the top quark was established at the LHC and many interesting results have been published since 2010. Improvements in precision for measurements would help PDF constraints and in testing higher order QCD calculations with new MC generators. Mass measurement of the top quark is connected to the Higgs originality with the W mass and deviation from the SM prediction appears by the BSM effect, as shown in Fig. 4.

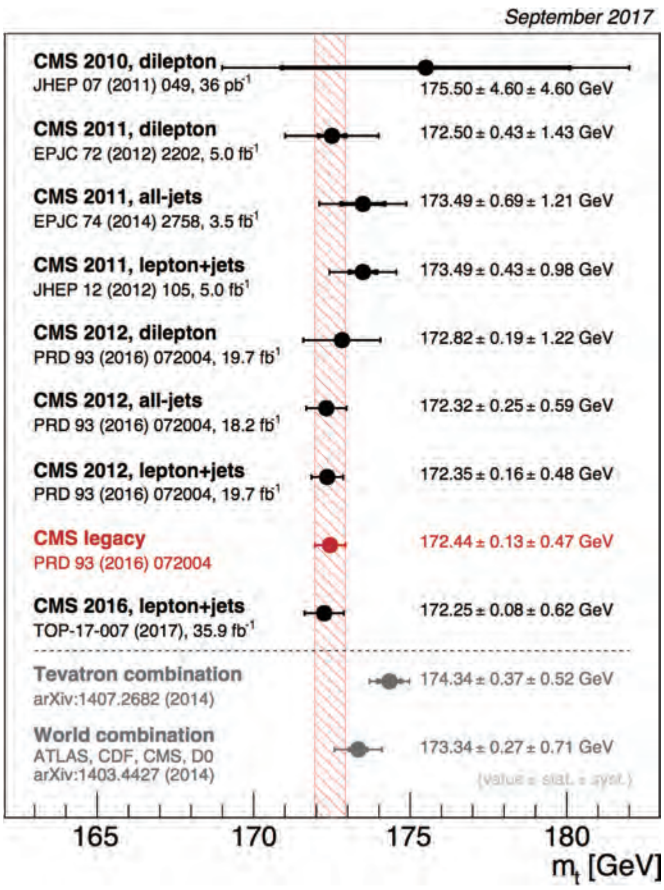

Fig. 12: Summary of recent top quark mass measurements from the CMS experiment and its combination with other experiments [12].

Fig. 12 shows the various results of top-quark mass measurements published recently, based on proton-proton data by the CMS experiment. The CMS legacy result obtained by the combination of the published CMS measurements is the most precise measurement of top quark mass to date, with a total uncertainty of 0.48 GeV.

FUTURE PROSPECTS

The LHC has plans to upgrade to the "High-Luminosity LHC (HL-LHC)". The main goal of this upgrade is to increase the instantaneous luminosity of the LHC machine (namely the number of collisions of bunch crossing) by a factor of five to ten. All detectors at the HL-LHC should be upgraded accordingly to collect proton-proton collision data under the environment of the upgraded LHC machine. At HL-LHC, radiation damage will be more significant than in the first phase of data-taking (which will last up to the year 2023) and the average pileup (number of interactions) is expected to be approximately 140. Most of subdetector components will be replaced and geometrical coverage of the detectors will be extended.

After completing the upgrade, the HL-LHC plans to start operation from 2026 and provide an additional integrated luminosity of about 2500 fb^{-1} over 10 years of operation. This amount of data would be almost 5-10 times larger than what we expect to collect at the first phase (up to 2023) of the data-taking. Such large amounts of data will give researchers great possibilities to study the phenomena discovered at the LHC and, in addition, those SM measurements will have sufficient amounts of datasets to probe the SM with extreme precision. Therefore, many interesting results are expected with this upgrade plan.

The approach of observing new physics through the study of rare decays like $B_s^0 \to \mu\mu$ will have benefits at the HL-LHC as high precision results will be possible due to the large amounts of datasets that the HL-LHC will provide. Also, $B_d \to \mu\mu$ will be measured with reasonable accuracy. The projected significant of $B_d \to \mu\mu$ is predicted

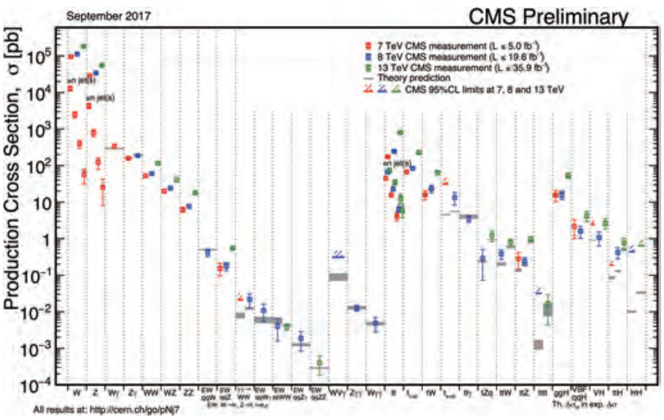

Fig.13: Summary of the cross section measurements of the SM processes [14].

to be 2.2 standard deviations with 300 fb^{-1} and 6.8 with 3000 fb^{-1} .

Precision measurements in the EWK sector and studies of processes that have good sensitivities to the EWK symmetry breaking would be improved with large statistics. The vector boson scattering and fusion processes, which have been discussed in a previous section, are expected to provide better sensitivities to new physics discoveries in this sector. Many additional interesting discussions regarding prospects for the HL-LHC and details of the detector upgrades are available in Ref. [13].

SUMMARY

We have discussed recent results for the SM precision measurements including W and Z boson, Drell-Yan, diboson and multiboson, multijets, b-quark and top-quark productions. Measurements introduced in this article have been accurately tested with the SM predictions and they represent the best achievements from the ATLAS, CMS and LHCb experiments at the LHC. Fig. 13 is the summary plot for the latest results of the cross sections for the SM processes in the CMS experiment. Such precision measurements provide an important test to understand the SM and to probe sensitive areas for BSM searches. New results will be continuously presented in the future and we anticipate that exciting observations may be identified by the results.

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